BACKGROUND OF THE INVENTION

(1) Field of the Invention

The invention relates to a voltage controlled variable capacitor, and more particularly, to a variable capacitor, formed of a larger number of fixed capacitor segments and a corresponding number of switching elements, which are typically integrated with the capacitance controlling functions on an integrated semiconductor circuit.

(2) Description of Prior Art

One example of a voltage-controlled capacitor is a varactor diode. When a reverse voltage is applied to a PN junction, it creates a depletion region, essentially devoid of carriers, which behaves as the dielectric of a capacitor. The depletion region increases as reverse voltage across it increases; thus the junction capacitance will decrease as the voltage across the PN junction increases. However the characteristics are non-linear and are widely temperature and process dependent. There is also a significant leakage current problem. Varactor diodes must be operated below the junction breakdown voltage. The varactor diode is sometimes called a varicap.

Fig. 1a shows the principle of a varactor diode; **Fig. 1b** shows the control voltage to capacitance characteristics of said varactor diode and demonstrates the effects of temperature and process variations. Another example is a switched capacitor chain, where capacitors are switched in parallel one after the other, thus increasing the capacitance step by step. The capacitors, when made of metal or polycarbonate structures, are far less sensitive to temperature and process deviations.

Fig. 2a shows the basic circuit concept. However, as is demonstrated in **Fig. 2b**, there is only a "step-wise linear" capacitance change over the control voltage. In addition the switching of the individual capacitors causes switching noise ("spikes") on the common circuit rails. Furthermore, while the switching transistor is kept in flat switching ramp to smooth the switching steps, the transistor's resistance causes a Q-factor problem.

U.S. Patent 6,356,135 (to Rastegar) describes an electronically trimable capacitor having a plurality of branch circuits, each including a capacitor which may be selectively controlled by a switch to contribute or not to the net capacitance exhibited by the trimable capacitor. Operation of the switches is under direction of digital instruction.

U.S. Patent 5,514,999 (to Koifman , et al.) shows a differential switched capacitor circuit, comprising: multiple switched capacitor stages, coupled in a chain.

U.S. Patents 4,449,141 and 4,456,917 (to Sato, et al.) disclose a variable capacitor comprising a plurality of variable capacitor elements each having depletion

layer control sections and a capacity reading section formed on a semiconductor substrate so that the capacity appearing at each capacity reading section varies in response to the bias voltage applied to the depletion layer control sections.

SUMMARY OF THE INVENTION

A principal object of the invention described in the present document is to control the capacitance of a variable capacitor in a strictly linear mode through a tuning voltage. A fundamental requirement is to achieve a high Q-factor at the same time.

The basic aspects of a mechanism to linearly control the capacitance of a variable capacitor in a linear mode through a tuning voltage are described in a related patent application. This related patent application, which is entitled " High Q linear controlled variable capacitor " (Document Nr. DS03-005A), is hereby incorporated by reference.

In accordance with the objectives of this invention, a circuit to implement a voltage controlled variable capacitor, operating in a linear mode and maintaining High Q-Factor is achieved. The invention disclosed in the referenced document DS03-005A added circuits and methods to linearize the capacitance change and to minimize the effect of parasitic resistance in the capacitor switching elements, which would degrade Q-factor. The herewith disclosed invention further implements a translinear amplifier

and adds additional circuits to further reduce the effect of parasitic resistance and of temperature deviation.

One key point to obtain highest possible Q-factor is to have at any time only one transistor in the active operating mode, i.e. RDSon–change-mode; all other transistors are either fully switched on or fully switched off.

Key element to achieve the goal of the invention is the introduction of a translinear amplifier into the signal path. Furthermore, functions to limit the switching-signal in order to drive the capacitor-switching element, typically a FET-transistor, into minimum RDSon or maximum RDSoff are added. Even further, a circuit to compensate the temperature effect of the capacitor switching device is added.

The translinear amplifier, typically with a gain of 1, compares a differential voltage at its inputs and provides the same differential voltage at its outputs; i.e. the output difference of said amplifier strictly follows the difference at said amplifier inputs, independent of the absolute voltage level at the outputs; input and output are perfectly decoupled. Said translinear amplifier can operate at different absolute voltage levels at their input and work independent at an output level, best suitable for said switching transistor's operation.

While the switching transistor is kept within its active switching mode (RDS changing mode) the resistance of the transistor linearly follows the input difference of said translinear amplifier. As said translinear amplifier can operate at different absolute

voltage levels at their input and output, the resulting level shifting operation is best suitable for said switching transistor's operation.

Additional circuit elements, described in the companion disclosure Document DS03-006, implementing a signal-limiting function, drive said switching transistor either into its fully-on state (RDSon going to 0) or drive it into its fully-off state (RDSoff going very high) when said switching device is outside its dedicated active working area.

There are various techniques to generate a set of reference values defining the threshold points for each of said amplifier stages. And there are various techniques to provide a tuning voltage, dedicated for the voltage controlled capacitance change, to all of said amplifier stages.

The total concept according to the proposed invention is shown in **Fig. 6**. One key point of the invention is the implementation of a signal-limiting function at both ends of the active switch operating area. Once the signal controlling the switching device leaves the dedicated active area, the signal condition is changed abrupt. **Fig. 7** visualizes this effect. The purpose is to drive said switching device to a fully-on state, when said switching device is outside its dedicated active working area on the lower resistance side and to drive said switching device to a fully-off status, when said switching device is beyond its dedicated active working area on the higher resistance side.

Depending on the technique to implement the reference values for each of the amplifiers within said translinear amplifier chain, even specific nonlinear relations of capacitance change versus tuning voltage can be constructed.

In accordance with the objectives of this invention, a set of individual capacitors is implemented. Such capacitors could, for example, be discrete metal or polymer capacitors on a common planar carrier or they could be integrated on a semiconductor substrate. The switching device is typically a FET transistor, which could be for example a P-MOS or N-MOS junction FET or a CMOS FET.

The amplifier primarily generating the control signal for the switching devices is, according to the invention, a translinear amplifier. In addition, a signal-limiting function, which is designed to drive said switching device to a fully-on status, when said switching device is outside its dedicated active working area on the lower resistance side or to drive said switching device to a fully-on status, when said switching device is outside its dedicated active working area on the lower resistance side, can be implemented. Such signal-limiting function could, according to the invention, be implemented within the translinear amplifier. It could however be implemented as separate circuit as well.

The circuit also provides the components to generate the set of reference voltages for the threshold voltages of each amplifier stage. A resistor chain is one possible solution. The amplifiers then use the tuning voltage supplied and said reference voltages to generate the control signal for said switching devices, which then switch the capacitors in parallel, one after the other.

Furthermore, the temperature deviation, caused by the temperature characteristics of the switching device can be compensated. One concept is to use a device of the identical type of the switching device to produce a temperature dependent signal and feed it as compensating voltage into the output reference point of the translinear amplifier. This will mirror the exact equivalent of the temperature error into the switching control signal and compensate its temperature error.

Even further, a specific non-linear characteristic of the tuning voltage to capacitance relation can be achieved by dimensioning the relation between said tuning voltage and said threshold points as desired. In one proposed solution, the individual steps of the reference resistor chain will be dimensioned to the desired nonlinear curve.

A translinear amplifier typically has a gain of 1. However, a gain different from 1 is also achievable, which, if implemented, gives one more degree of freedom in dimensioning the circuit parameters. For example, the remaining overlapping of neighboring capacitor switching stages may be even further reduced.

In accordance with the objectives of this invention, a method to control the capacitance of a variable capacitor in a strictly linear mode through a tuning voltage and to achieve a high Q-factor at the same time generate, is achieved. One method is to switch a variable number of capacitors in parallel, where only one is in the active transition phase of being switched on in a continual mode. All other capacitors of a larger number of capacitors are either already fully switched on or are still complete switched off. One key method is to linearly control the switching function for each of

said continual switching devices, when said switching device is in its dedicated active working area in a linear mode, but to change the signal abrupt, as soon as the control signal for said switching function leaves its dedicated active working area. One method drives said switching device to a fully-on status, when said switching device is outside its dedicated active working area on the lower resistance side. A similar method drives said switching device to a fully-off status, when said switching device is beyond its dedicated active working area on the higher resistance side. A further method amplifies, by the means of a translinear amplifier, the difference of the capacitance tuning voltage and the reference voltage of each amplifier stage, producing the linear control signal for said continually switching operation. Another method generates a set of reference values, one for each of said amplifier stages. Finally, the circuit supplies a tuning voltage, dedicated for the voltage controlled capacitance change, to all of said amplifier stages.

A further method compensates the temperature effect of the switching device. It generates a temperature dependent compensation voltage by using an identical device-type as the switching device and feeds the resulting signal into the output reference point of the translinear amplifier

An even further method is to produce threshold points (or reference points) along a non-linear curve and getting a desired non-linear relation of the total capacitance changes versus tuning voltage.

Even more, with a translinear amplifier with a gain different from 1, the whole concept gains one more degree of freedom in optimizing certain operating parameters, like the overlapping of neighboring switching stages.

BRIEF DESCRIPTION OF THE DRAWINGS

In the accompanying drawings, forming a material part of this description, there is shown:

Fig. 1a (Prior Art) shows a simplified structure of a varactor diode.

Fig. 1b (Prior Art) shows the relation of the capacitor over tuning voltage change and shows the effects of temperature and process variation.

Fig. 2a, and 2b (Prior Art) shows a principal circuit of a switched capacitor chain and the relation of the capacitor over tuning voltage change.

Fig. 3 shows a circuit with operational amplifiers in the control signal path and with a chain of resistors as reference voltage circuit.

Fig. 4a shows the gate voltage versus tuning voltage relation for the series of capacitor switching stages, according to Fig. 3.

Fig. 4b visualizes the signal overlapping effect of the switching operations of just 2 stages of the circuit according to Fig. 3.

Fig. 5 shows the principal circuit arrangement of a single capacitor switching stage with a translinear amplifier.

Fig. 6 shows the circuit schematic of multiple capacitor switching stages with a chain of translinear amplifiers, in accordance with an embodiment of this invention.

Fig. 7 visualizes said switching transistor's gate voltage versus capacitor tuning voltage dependency of a single stage.

Fig. 8 visualizes said switching transistor's gate voltage, versus capacitor tuning voltage dependency of a multiple stages.

Fig. 9 shows a realistic circuit diagram of an implementation, in accordance with an embodiment of this invention.

Fig. 10 shows the added circuit to generate a temperature compensated reference voltage.

Fig. 11a demonstrates the resulting capacitance versus tuning voltage for multiple capacitor switching stages, according to Fig. 6.

Fig. 11b demonstrates the resulting Q-factor versus tuning voltage for multiple capacitor switching stages, according to Fig. 6.

Fig. 12 demonstrates 2 possible variations of capacitance versus tuning voltage characteristics.

Fig. 13 visualizes the methods to control the capacitance of a variable capacitor in a strictly linear mode through a tuning voltage and achieving a high Q-factor.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

The objectives of this invention are to control the capacitance of a variable capacitor in a strictly linear mode through a tuning voltage. A fundamental requirement is to achieve a high Q-factor at the same time.

A discussion of the general principles of a voltage controlled variable capacitor with linear characteristic, formed of a larger number of fixed capacitor segments and a corresponding number of switching elements, using operational amplifiers is disclosed in the related patent application DS03-005A, the entire contents of which is incorporated herewith by reference.

Fig. 3 shows a principal circuit diagram of the referenced related patent application. **Amp 1** to **Amp n** are said operational amplifiers, **Sw 1** to **Sw n** are the switching devices and **Cap 1** to **Cap n** are said capacitors that will be switched in parallel. As an example, a resistor chain **R1** to **Rn**, or a similar circuit, produces a series of voltage references **Ref 1** to **Ref n** and each of said operational amplifiers compares the tuning voltage input with its dedicated reference voltage. The resulting variable capacitance is available at the output points **varCap**.

A detailed view on the individual ramp-up functions at the switching transistor's gate, of the circuit according to Fig. 3, is shown in **Fig. 4a**. **Vg1** to **Vg7** are the gate

voltage versus tuning voltage slope of the switching stages number 1 to 7 in this example. One can assume the active area of RDS changing to be between the 2 % point and the 98 % point. All slopes of the individual gate voltages are strictly parallel. Threshold points **Th1** to **Th7** in **Fig. 11** are equally spaced (distances **d1** to **d7** in **Fig. 4a**). **Fig. 4b** visualizes the overlapping switching operations of just 2 adjacent stages of the circuit according to Fig. 3. **Overlap** is a measure, where **Vg2** just starts to switch on stage number 2 and where **Vg1** is still in the active working range for stage number 1. Because said gate voltage versus tuning voltage slopes are all in parallel, all overlaps are the same.

According to the objectives of this invention, the operational amplifiers as shown in **Fig. 3**, are replaced by translinear amplifiers. A single stage of said capacitor switching function is presented in **Fig. 5** and the total circuit schematic for multiple stages according to the proposed invention is shown in **Fig. 6**. Key advantage is the fact, that the voltage levels at the translinear amplifier inputs and at the translinear amplifier outputs are independent, only the differential voltage at the inputs and at the outputs is important. It works in this context as a level shifter. Such translinear amplifiers have typically a gain of 1.

The translinear amplifier in **Fig. 5** compares the differential voltage at its inputs **Vinp-5** and **Vinn-5** and, through various current mirroring techniques, provides the same differential voltage at its outputs **Voutp-5** and **Voutn-5**; i.e. the output difference of said amplifier strictly follows the difference at said amplifier inputs, independent of the absolute voltage level at the outputs. The translinear amplifier then drives said current

switching device **N1-5** with the gate voltage **Vg-5** to linearly switch on said individual small capacitor **Cap-5**.

Within a chain of said translinear amplifiers, each one can operate at a different absolute voltage level at their input and work independent at another output level. In this way the network to generate the reference voltages can be optimized independently for each stage, because the voltage level best suitable for the control operation of each switching transistor can be freely selected. In the circuit shown in **Fig. 6** as an example, the reference voltages are produced in a simple chain of resistors. The translinear amplifiers **Tr.Amp 1** to **Tr.Amp n** can adjust between said input reference voltage levels **Ref-in 1** to **Ref-in n** and the output reference levels **Ref-out-1** to **Ref-out-n**. Said translinear amplifiers then control the switching transistors **Sw 1** to **Sw n**, which in turn linearly switch on the individual small capacitors **Cap 1** to **Cap n**.

Another key point of the invention is the implementation of a signal-limiting function at both ends of the active switch operating area. As long as the switching transistor is kept within its active switching mode (RDS changing mode) the resistance of the transistor linearly follows the input difference of said translinear amplifier. Once the signal controlling the switching device leaves the dedicated active area, the signal condition is changed abrupt. **Fig. 7** visualizes this effect. The purpose is to drive said switching device to a fully-on state, when said switching device is outside its dedicated active working area on the lower resistance side and to drive said switching device to a fully-off status, when said switching device is beyond its dedicated active working area on the higher resistance side. Additional circuit elements, implementing said signal-

limiting function, drive said switching transistor either into its fully-on state (RDSon going to 0) or drive it into its fully-off state (RDSoff going very high) as soon as said switching device falls outside its dedicated active working area. Such signal-limiting function could, according to the invention, be implemented within said translinear amplifier circuit. It could however be implemented as separate circuit external to said translinear amplifier as well.

Fig. 7 visualizes the idea of sharply cutting off said signal controlling the switching device as soon as the Gate **Control Voltage Vg-7** leaves the dedicated active area, when the **Tuning Voltage Vctl** changes. For example, beyond the 98 % on-point, said signal **Vg-7** controlling the switching device rises sharply and below the 2 % off-point said signal **Vg-7** controlling the switching device is driven to rapidly switch-off. **Fig. 8** presents the same behavior as Fig. 7 for a larger number of said capacitor switching stages. **Th1** to **Thn** are the selected threshold points for said switching to occur. **d1** to **dn** are the distances of said threshold points, that normally are dimensioned to equal distance.

Fig. 9 shows a realistic circuit diagram of an implementation, in accordance with an embodiment of this invention. **Tr.Amp 1** to **Tr.Amp n** are said translinear amplifiers, **Sw 1** to **Sw n** are the switching devices and **Cap 1** to **Cap n** are said capacitors that will be switched in parallel, resulting in the total capacitance **varCap**. **R1** to **Rn** build the resistor chain to produce references voltages for the amplifier of each stage, as already shown in Fig. 6.

Furthermore, a concept of this disclosure is to compensate the temperature deviation, caused by the temperature characteristics of the switching device; **Fig. 10** presents this concept. One method is to use a device **N2-10** of the identical type of the switching device **N1-10** to produce a temperature dependent signal and feed it as compensating voltage **Vref-10** into the output reference point **Voutn-10** of the translinear amplifier. This will mirror the exact equivalent of the temperature error into the switching control signal **Vg-10** and compensate its temperature error.

The total capacitance versus tuning voltage characteristic for a circuit with n-stages is demonstrated in **Fig. 11a** and the overall characteristic of said Q-factor is presented in **Fig. 11b**

Depending on the technique to implement the reference values defining said threshold points for each of the amplifiers within said translinear amplifier chain, even specific nonlinear relations of capacitance change versus tuning voltage can be constructed. The concept is demonstrated in **Fig. 12**, with **Curve A** and **Curve B** as examples.

In accordance with the objectives of this invention, a set of individual capacitors is implemented. Such capacitors could be discrete metal or polymer capacitors on a common planar carrier or they could be integrated on a semiconductor substrate. The advantage of a capacitor not being of the junction (diode) type capacitor is the invariance due to voltage or temperature at the capacitor. The switching device is typically a FET transistor, which could be for example a P-MOS or N-MOS junction FET

or a CMOS FET. In the case complementary components are used all voltage levels would just be inverted without changing the principals of operation.

The method to achieve the objectives of this invention is illustrated in **Fig. 13**. First **(80)**, it starts with just the first capacitor, i.e. the count n=1 **(81)**. When the tuning voltage is rising **(82)** or is high enough **(83)**, the amplifier ramps up **(85)** and the switching device linearly switches on capacitor element n **(87)**. If the tuning voltage continues to rise **(90)** the amplifier continues to ramp up **(91)**. If however the tuning voltage turns down **(90)**, the amplifier will ramp down as well **(92)**. Once the tuning voltage reaches the upper limit of the active switching area **(95)**, the switching device of stage n is fully switched on **(97)** and the process continues with the next step n = n + 1 **(99)(101)**. Depending on the direction of continued voltage change **(103)** it continues to ramp up or down. In case tuning voltage is lower than maximum for stage n **(84)**, the amplifier ramps down **(86)** and the switching device linearly switches on capacitor element n **(88)**. Once the tuning voltage reaches the lower limit of the active switching area **(96)**, the switching device of stage n is fully switched on **(98)** and the process continues with the next step n = n + 1 **(100)(102)**. Again, depending on the direction of continued voltage change **(103)** it continues to ramp up or down and restarts at **(82)**.

While the invention has been particularly shown and described with reference to the preferred embodiments thereof, it will be understood by those skilled in the art that

various changes in form and details may be made without departing from the spirit and scope of the invention.

What is claimed is: